

Stable or Unstable Light Dark Matter

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Abstract

We consider the case of light dark matter (~ 10 GeV). We discuss a simple Z_2 model of scalar self-interacting stable dark matter, as well as a related model of unstable long-lived dark matter which can explain the anomalous Kolar events observed decades ago.

Searches for the dark matter (DM) of the Universe have so far not yielded unambiguous results. Whereas experimental efforts have concentrated on the 100 GeV range of DM masses, there are hints that it may actually be much lighter, say ~ 10 GeV. One intensely studied scenario at present [1] comes from the observation of gamma rays originating in the galactic center, which may be due to the annihilation of dark matter of mass ~ 30 GeV to $b\bar{b}$ or of mass ~ 10 GeV to $\tau^-\tau^+$. There is also another much less known hint coming from the anomalous Kolar events [2, 3] recorded in underground detectors in the 70's and 80's, which have recently been interpreted [4] as being due to the decays of DM with mass in the range of 5-10 GeV.

In this paper we consider the case of light dark matter (~ 10 GeV) which is stable or unstable. We discuss two minimal examples. The first involves a complex scalar $\zeta = (\rho + i\sigma)/\sqrt{2}$, such that σ is stable DM and ρ is a light mediator for the self interactions of σ . The second has additional singlet charged fermion E and singlet neutral scalar η such that σ becomes unstable and decays dominantly to $\mu^-\mu^+$ in one loop with the correct lifetime to explain the anomalous Kolar events.

(I) We consider first the model of a complex neutral scalar ζ interacting with the standard model (SM) Higgs doublet $\Phi = (\phi^+, \phi^0)$. Let the scalar potential be given by

$$V = \mu_1^2 \Phi^\dagger \Phi + \mu_2^2 \zeta^* \zeta + \frac{1}{2} \lambda_1 (\Phi^\dagger \Phi)^2 + \frac{1}{2} \lambda_2 (\zeta^* \zeta)^2 + \lambda_3 (\Phi^\dagger \Phi) (\zeta^* \zeta), \quad (1)$$

so that ζ is protected by a $U(1)_D$ symmetry. If $U(1)_D$ is unbroken, ζ is a possible DM candidate. However, its mass μ_2 and coupling λ_3 are constrained by three conditions: (1) its thermal relic abundance, (2) the upper limit on its elastic scattering cross section off nuclei in direct-search experiments, and (3) the invisible decay $h \rightarrow \zeta^* \zeta$ if $m_\zeta < m_h/2$ where h is the one Higgs boson of the SM, identified as the 125 GeV particle discovered [5, 6] at the Large Hadron Collider (LHC) in 2012. Note that these are the same conditions if $U(1)_D$ is replaced by Z_2 and ζ by a real scalar singlet [7]. As such, for $m_\zeta = 10$ GeV, it is definitely

ruled out [8].

We now add the term

$$V' = \frac{1}{2}\mu_3^2\zeta\zeta + H.c. \quad (2)$$

Without loss of generality, we choose μ_3^2 to be real, and define

$$\zeta = \frac{\rho + i\sigma}{\sqrt{2}}. \quad (3)$$

We then have

$$V' = \frac{1}{2}\mu_3^2(\rho^2 - \sigma^2). \quad (4)$$

This means that $U(1)_D$ is softly broken to $Z_2 \times Z_2$. This scenario does not differ qualitatively from the unbroken one and is also ruled out.

We now allow the Z_2 symmetry associated with ρ be broken spontaneously with $\langle \rho \rangle = u$ and redefine ρ as $u + \rho$. Together with replacing Φ with $(0, (v + h)/\sqrt{2})$, we obtain the minimization conditions for $V + V'$:

$$\mu_1^2 + \frac{1}{2}\lambda_1 v^2 + \frac{1}{2}\lambda_3 u^2 = 0, \quad (5)$$

$$\mu_2^2 + \mu_3^2 + \frac{1}{2}\lambda_2 u^2 + \frac{1}{2}\lambda_3 v^2 = 0. \quad (6)$$

As a result, after dropping a constant term,

$$\begin{aligned} V + V' &= \frac{1}{2}\lambda_1 v^2 h^2 + \frac{1}{2}\lambda_2 u^2 \rho^2 + \lambda_3 v u h \rho - \mu_3^2 \sigma^2 \\ &+ \frac{1}{2}\lambda_1 v h^3 + \frac{1}{2}\lambda_2 u \rho(\rho^2 + \sigma^2) + \frac{1}{2}\lambda_3 v h(\rho^2 + \sigma^2) \\ &+ \frac{1}{8}\lambda_1 h^4 + \frac{1}{8}\lambda_2(\rho^2 + \sigma^2)^2 + \frac{1}{4}\lambda_3 h^2(\rho^2 + \sigma^2). \end{aligned} \quad (7)$$

Hence $m_\sigma^2 = -2\mu_3^2$ may be chosen to be 10 GeV and be DM because it is still protected by an unbroken Z_2 symmetry. Its coupling to h , i.e. λ_3 , may be chosen to be very small to satisfy the direct-search bound. As for its relic density, we now have another annihilation channel to consider, i.e. $\sigma\sigma \rightarrow \rho\rho$, as shown in Fig. 1. The mass-squared matrix spanning h

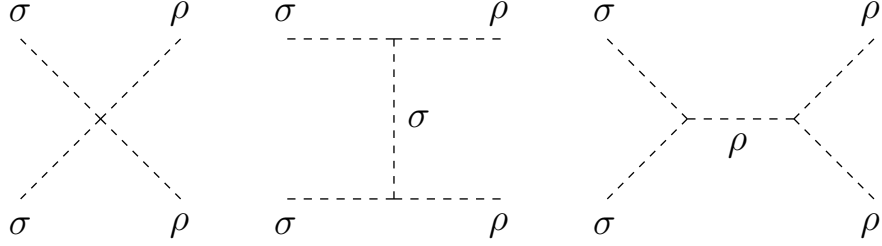


Figure 1: $\sigma\sigma$ annihilation to $\rho\rho$ final states.

and ρ is given by

$$\mathcal{M}_{h\rho}^2 = \begin{pmatrix} \lambda_1 v^2 & \lambda_3 v u \\ \lambda_3 v u & \lambda_2 u^2 \end{pmatrix}. \quad (8)$$

We look for a solution where $h - \rho$ mixing is small, with two mass eigenvalues such that one is 125 GeV and the other 10 MeV. The latter may then act as a suitable scalar mediator for σ as self-interacting dark matter [9]. Since λ_3 is already assumed to be small, the mixing $(\lambda_3/\lambda_1)(u/v)$ will not be significant. Hence ρ is essentially a mass eigenstate with $m_\rho^2 \simeq \lambda_2 u^2$ and the amplitude of Fig. 1 is given by

$$\mathcal{A} = \lambda_2 - \frac{\lambda_2^2 u^2}{4m_\sigma^2} = \lambda_2 \left(1 - \frac{m_\rho^2}{4m_\sigma^2} \right), \quad (9)$$

and the annihilation cross section \times relative velocity is

$$\sigma \times v_{rel} = \frac{\mathcal{A}^2}{64\pi m_\sigma^2}. \quad (10)$$

Setting this to the optimal value [10] $2.2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ for the correct dark-matter relic density of the Universe, we find for $m_\sigma = 10 \text{ GeV}$ and $m_\rho = 10 \text{ MeV}$,

$$\lambda_2 = 0.006, \quad u = 0.13 \text{ GeV}. \quad (11)$$

Once produced, ρ achieves thermal equilibrium with the SM particles through its mixing with h and decays mainly to e^-e^+ pairs.

To explain [4] the anomalous Kolar events, σ must decay with a lifetime slightly greater than the age of the Universe. Its decay product should also be mostly muons. To make σ

unstable, one option is to add the trilinear term

$$V'' = \mu_4 \Phi^\dagger \Phi \zeta + H.c. \quad (12)$$

This induces $h - \sigma$ mixing given by $\sqrt{2}Im(\mu_4)/\lambda_1 v$, which is then arbitrarily chosen to be extremely small ($\sim 10^{-19}$) so that the σ decay lifetime is of order the age of the Universe. Even so, its decay must still go through h and thus mainly into $\tau^- \tau^+$. The branching fraction of τ to μ diminishes the number of observable events to only a few percent, which is not a desirable scenario for a robust explanation of the Kolar events, but cannot be ruled out with the meager data at hand.

(II) To obtain a naturally suppressed lifetime and a dominant decay to muons, we now consider the following addition to our $U(1)_D$ model. We add two new fields: negatively charged fermion $E_{L,R}$ and neutral complex scalar η , each transforming as $1/2$ under $U(1)_D$. As a result, we have the possible new interactions:

$$\begin{aligned} \mathcal{L}' &= f \bar{E}_L \mu_R \eta + \mu_5 \zeta^* \eta \eta + H.c. \\ &= \frac{f}{\sqrt{2}} \bar{E}_L \mu_R (\eta_R + i\eta_I) + \frac{f}{\sqrt{2}} \bar{\mu}_R E_L (\eta_R - i\eta_I) \\ &+ \frac{\mu_5 u}{2\sqrt{2}} (\eta_R^2 - \eta_I^2) + \frac{\mu_5}{2\sqrt{2}} \rho (\eta_R^2 - \eta_I^2) + \frac{\mu_5}{\sqrt{2}} \sigma \eta_R \eta_I, \end{aligned} \quad (13)$$

where $\eta = (\eta_R + i\eta_I)/\sqrt{2}$ and μ_5 has been chosen real by absorbing the arbitrary phase of η . This implies

$$m_R^2 - m_I^2 = \frac{\mu_5 u}{\sqrt{2}}, \quad (14)$$

and σ decays into $\mu^- \mu^+$ as shown in Fig. 2. The effective coupling of $\sigma \bar{\mu} \gamma_5 \mu$ is then given by

$$f_{eff} = \frac{f^2 \mu_5^2 u m_\mu}{128 \pi^2 m_E^4} \left[\frac{-2 - 5x + x^2}{6x(1-x)^3} - \frac{\ln x}{(1-x)^4} \right], \quad (15)$$

where $x = m_\eta^2/m_E^2$. Note that f_{eff} is highly suppressed for large m_E and would be zero if $m_R = m_I$, i.e. $u = 0$. The decay width of σ is

$$\Gamma_\sigma = \frac{m_\sigma f_{eff}^2}{8\pi}. \quad (16)$$

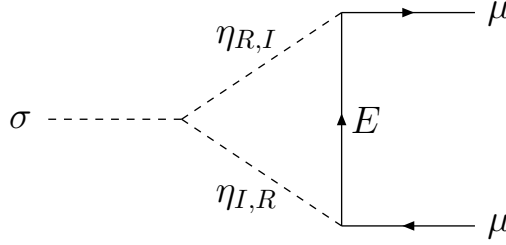


Figure 2: One-loop σ decay to $\mu^-\mu^+$.

For $\tau_\sigma = 1/\Gamma_\sigma$ to be the lifetime of the Universe, i.e. 13.82 billion years, we need

$$f_{eff} \simeq 2 \times 10^{-21}. \quad (17)$$

In the limit $x = 1$, the bracket has the value $-1/12$. Consider for example $m_E = 1$ TeV, $u = 0.13$ GeV, $\mu_5 = 1$ GeV, then the above value of f_{eff} is achieved with $f = 0.044$.

So far we have assumed that only μ couples to E . It is clear that e or τ may do so as well. Note also that in this model, there is still an exactly conserved Z_2 symmetry, under which η_R, η_I and E are odd, with all other particles even. Suppose η_R is the lightest, then its relic density is determined by its interaction with the SM Higgs boson h through the $\lambda_4(\eta^*\eta)(\Phi^\dagger\Phi)$ term. We assume that λ_4 is large enough, so that the η_R relic density is negligible. This then opens up the possibility for the unstable σ to be a light dark-matter candidate which also explains the anomalous Kolar events.

To conclude, we have discussed the case of stable or unstable light (~ 10 GeV) dark matter based on an $U(1)_D$ symmetry which is consistent with present constraints. The simplest model where $U(1)_D$ breaks to exact Z_2 with a complex scalar singlet allows stable self-interacting dark matter. It may also allow unstable dark matter, which decays into $\tau^-\tau^+$ through an extremely small mixing ($\sim 10^{-19}$) with the Higgs boson. An alternative is to add one heavy charged fermion singlet and one heavy neutral scalar singlet (both ~ 1 TeV) transforming under $U(1)_D$ such that the dark matter may decay in one loop dominantly into

$\mu^- \mu^+$ with a highly suppressed rate, resulting in a lifetime just greater than the age of the Universe to explain [4] the anomalous Kolar events [2, 3] observed decades ago.

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